FINAL REPORT

CONTRACT AF49(638)-201

THEORETICAL AND EMPIRICAL STUDIES OF THE BASIC STRUCTURE OF TURBULENT SHEAR FLOWS, INCLUDING GENERALIZED THERMOKINETIC APPROACHES

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I. PREFACE

This report has been prepared to assist in the transition from contract to grant status; the work is continuing, and therefore this report should not be interpreted as a final report on the research. The detailed research results of this work are reported in AFOSR Technical notes and standard periodicals. Herein we present a summary of the work covering: (a) basic objectives, (b) landmarks of progress during life of AF49(638)-201 and (c) summary of continuation of work under AF Grant AF-AFOSR-136-63. A report of publications to date and in progress is also given.

II. OBJECTIVES

The objectives of the research under AF49(638)-201 center on problems of flow in adverse pressure gradients and include: structure of turbulent shear layer, diffuser performance and design, flow separation, and problems in detailed and gross flow stability. A spectrum of researches from pure research through applied research to the point of design utility are closely integrated. Only the more basic aspects have been supported from AFOSR funds; all are reported due to the close working relations maintained; support sources are indicated in detail in status reports, proposals and annual inventories on file with Mechanics Division AFOSR. The long range goals of these researches are:

(i) understanding and detailed data on the flow model of the turbulent shear layer over a wide range of conditions. The end use of this data and knowledge is construction of a rational theory for turbulent shear layers; none now exists.

(ii) Construction of sound methods for rational channel design. Since the flow in favorable pressure gradients is now manageable; the central problem is that of adverse pressure gradient flows, that is, diffusers.

(iii) Understanding of general stability problems in dynamic field situations. Initial interest was stimulated by the fluid mechanical problems involved, but the theoretical researches have been necessarily broadened to include a much greater variety of systems. Empirical studies of gross stability in fluid systems have also been carried out, and are continuing.

III. Landmarks in the Stanford Internal Flow Program during the life of AF49(638)-201.

1958 Publication of the "flow regime chart" for straight walled Subsonic Diffusers. -- This chart allows for the first time simple and accurate prediction of the real flow regimes for the broad class of diffusers covered.

Development of optimum Design Procedures based on the correlation of the flow regime chart and performance.

Publication of Design criteria using vane systems based on the flow regime chart to produce efficient wide angle diffusers at angles of divergence up to 40 degrees.

Discovery of the flow model of the "wall layers" of the turbulent shear layer. Completion of a preliminary survey of it, and construction of the concept of its role in the maintenance of turbulence in bound shear layers.

1959 First systematic studies of the effects of inlet conditions on performance of straight-walled diffusers completed.

Construction of special low speed water apparatus for study of flow models in turbulent shear flows and separated flows.

1960 Use of "wall layer model" and its physical implications to construct improved separation criteria (with V. A. Sandborn).

Completion of study of simple methods for construction of similarity solutions for partial differential equations.

Completion of first systematic study of flow regimes in a family of curved diffusers.

1961 Establishment of the non-dimensional correlation of transverse spacing in the wall layers of the turbulent shear layer.

Establishment of quantitative relation between observed "flow model" and each of the four zones of the well known "universal" velocity correlation for the turbulent shear layer on a flat plate.

Disclosure of many additional details of flow models in later stages of laminar-turbulent transition. Establishment that "wall model" of the same type and transverse spacing exists in turbulent spots as in fully turbulent flow.

Mapping of flow over single and double backward facing steps. Demonstration that the controlling factor in setting the overall flow geometry with large stall present is the mixing properties of the free shear layer between the stall region and the mainstream.

Completion of quantitative data map for straight-walled, two-dimensional, diffusers over a wide range of conditions; construction of reliable machine program for prediction of performance in unstalled region.

Completion of tests in curved diffusers and rotating systems showing the importance of body forces on the wall layer model of the bound shear layer and hence on transition and separation. Design of large rotating test apparatus for further study.

1962 Completion and checking of a preliminary theory for the wall layer flow in a bound turbulent shear layer based on observed flow models and using appropriate expansion in parameters. Delineation of a critical test for the theory.

Development of new marker techniques using hydrogen bubbles in water to show the entire velocity field at an instant in any plane containing the flow direction. Use of this method for a NCFMF teaching movie and also to obtain good measurements of the mean velocity of the low speed "streaks" which form a key portion of the wall layer model.

Establishment of "preferred" trajectories and approximate distribution functions for eddies ejected from the wall model of the turbulent shear layer.

Completion of theory providing a two-fold generalization of Gortler solution to the two-dimensional free shear layer to include effects of longitudinal pressure variation and non-zero velocity on the low speed side.

Completion of a reliable and reasonably accurate hot-wire anemometer for low speed water flow. Use of this instrument to check the generalized solution for the free jet flows, the derived transformation of velocity relating the solutions to the zero velocity ratio case, and the use of Prandtl's mixing hypothesis to free shear layers with pressure gradients.

Establishment of more general variational theorems for thermokinetic systems obeying Pfaffian Gibbsian forms; demonstration that no single variational principle exists for the most general cases where properties vary in a steady state field with dissipation.

Extension of design criteria for use of vanes to produce efficient wide angle diffusers to total angles of 80 degrees.

Completion of outline of Diffuser Design Manual.

Completion and checking of computing program for rational design of arbitrary channels. Construction of air unit to test results of program and establish design limits for curved channels in the regions where previous tests (1960) show simple design procedures give poor results.

Completion of a successful computing procedures for calculation of hydrodynamic stability of disturbances growing in space (as opposed to all previous procedures which have computed growth at a point in time). Flow model observations show the actual behavior involves growth in space both in transition breakdown and in the interaction between the wall models of the bound turbulent shear layer and the outer portions of the layer.

IV. FURTURE WORK

Since the Stanford Internal Flow Program is a continuing fundamental research program, the change to grant status in no way implies completion of all projects in motion. We expect to continue the diffuser studies in order to extend the results to more classes of systems and to include body forces. This work will proceed along now well developed and highly successful lines of research. The ultimate goal is completion of the diffuser design manual; copy showing status attached. We also expect to push vigorously the work on bound shear layers and separated flows. Three aspects of this bear special mention.

Current marker techniques and hot-wire instrumentation in water are being used to extend model information on the bound shear layer into pressure gradient cases, to obtain more model details, and to make improved quantitative measurements of mean speed and distribution functions for the eddy trajectory. Work on these problems, although not completed, is sufficiently advanced that we have begun serious work on construction of rational theories for the outer portion of the shear layer to augment the theoretical work already done on the wall layers. As repeatedly emphasized, the problem is complex and difficult, but also fundamental and of great technological significance. Progress has been slow but steady, and we remain optimistic that real progress toward construction of rational predictive methods can be achieved along the general lines of research we have been pursuing.

It will be noted that during 1961 and 1962 the program began to move out of the purely empirical and into the mathematical predictive stage in several areas of work. This has actually occurred to a greater degree than reported since the efforts of the past three or four years towards increasing background in special mathematical techniques is only currently beginning to bear fruit. The methods developed have already resulted in several "by-products" in the form of solutions to problems of space (low-gravity environments) of distinct utility to the Air Force. We anticipate increased development of quantitative predictive techniques and analytical results during the near future.

The work on fully stalled flows (1960) showed that at least a key missing piece of information was the mixing properties of the free shear layer between the stalled region and the mainstream. At that time, 1960, the only available solution for such layers was for a zero pressure gradient and zero ratio of free stream velocities. Neither of these conditions obtain in most stalled flows. Since that time work has gone forward very rapidly, and a solution for both these effects has been obtained and checked. This solution opens many possibilities. One immediate possibility is the construction of a rational theory for design of at least many jet ejectors; no such theory now exists for these widely used devices. Application of the solution to stalled flows, that is flows with large separated regions, will be more difficult. We anticipate early attempts at solution to certain simple cases, which we call fully stalled flows, with a reasonable expectation of success.

Although progress has been steady, much remains to be done.

APPENDIX I List of Publications From Stanford Internal Flow Program

No.	Author	Date	Title	Contract or Grant
MD-1	S.J.Kline	3/15/57	Some new mechanisms and conceptions of stall including the behavior of vaned and unvaned diffusers	Naw-6500
MD-2	S.J.Kline A.V.Lisin B.A.Waitman	5/15/58	An experimental investigation of the effect of free stream turbulence on the turbulent boundary layer	Naw-6500
MD-3 (AFOSR-TN-58-160)	S.J.Kline P.W.Runstadler	6/58	Some preliminary results of visual studies on the flow model of the wall layers of the turbulent boundary layer	AF49(638) 295
MD-4 (AFOSR-TN-58-637)	S.J.Kline	5/58	On the nature of stall	AF49(638) 201, 295
MD-5 (AFOSR-TN-890)	D.E.Abbott S.J.Kline		Theoretical and experimental investigation of flow over single and double backward facing steps	AF49(638) 201
MD-6 (AFOSR-TN-60-1163)	D.E.Abbott S.J.Kline	10/60	Simple methods for classifaction and construction of similarity solutions of partial differential equations	AF49(638) 201
MD-7 (AFOSR-TN-1875)	S.J.Kline K.A.Meyer	12/61	Visual study of the flow model in the later stages of laminar-turbulent transition on a flat plate	AF49(638) 201
PD-1	C.A.Moore S.J.Kline	8/54	Investigation of air-foils, plates, grids, and rods for boundary layer control in subsonic diffusers	Naw-6317

No.	Author	Date	Title	Contract or Grant
PD-2	C.A.Moore S.J.Kline	9/55	Some effects of vanes and of turbulence on two-dimensional wide-angle subsonic diffusers	Naw-2317-6404
PD-3	D.L.Cochran	4/57	The use of short flat vanes for producing efficient wide-angle two-dimensional subsonic diffusers	Naw-6404,6500
PD-4	S.J.Kline D.E.Abbott R.W.Fox (AFOSR-TN-58-638)	6/58	Optimum design of straight-walled diffuser	AF49(638) 201, 295
PD-5	B.A.Waitman L.R.Reneau S.J.Kline	3/60	Effects of inlet conditions on performance of two-dimensional diffusers	GE Company
PD-6	R.W.Fox S.J.Kline	8/60	Flow regime data and design methods for curved subsonic diffusers	Worthington Corporation
PD-7	O.G.Feil	2/62	Vane systems for very wide angle subsonic diffusers	Worthington Corporation

APPENDIX II Outline of Diffuser Design Manual

Introduction: (Kline and Johnston)

Will set forth the goals; discuss dates and form of publication; indicate areas where more research is needed to fill gaps in our knowledge; set forth our philosophy of research in Internal Flow.

Section I (Reneau, Kline and Johnston)

Two-Dimensional, Straight Diffusers.

Chapter 1 - Flow regimes and stall in internal flow.

Chapter 2 - Basic performance data.

Chapter 3 - Diffuser Design - In this chapter will be discussions of various design problems, and recommendations for design based on stall limits and performance limits over the whole range of present knowledge.

Chapter 4** The control of stall - herein will be outlined the presently known methods for stall control and improvement of performance of badly stalled diffusers.

Chapter 5 - Introduction to theoretical methods of stall and performance prediction - General discussion of possible theoretical models for the several regimes in light of available observations.

Chapter 6 - Theory for unstalled diffusers with thin inlet boundary layers.

Chapter 7 - Prediction of the effects of variation of geometric parameters (Aspect Ratio, wall shape, etc.) on performance of unstalled diffusers.

Chapter 8** Theory for fully stalled diffusers.

Chapter 9** Correlation of performance data in the large transitory stall regime using available theory (Chapters 6 and 8) to establish the limits of correlation.

Section II (Sagi, Kline and Johnston)

Two-Dimensional Diffusing Channels; Curved Diffusers.

Chapter 1 - Flow Regimes and Stall - Circular arc centerline geometry; application of straight wall diffuser stall limits to the design of curved diffusers; effects of wall curvature on boundary layer structure and stall, effects of secondary flows from end walls.

Chapter 2 - Development of a wall loading distribution criteria applicable to curved diffuser design - Basic requirements for wall velocity distribution for potential flow design of curved diffusers; water table tests on the effects of straight diffuser wall fairing on first stall limit; application of results to curved diffuser design.

Chapter 3 - Performance of Curved Diffusers at and around the first stall design point for faired-wall, straight centerline diffusers and curved diffusers.

Chapter 4 - Curved Diffuser Design - Discussion of various design problems and recommendation for stalling and performance limits.

Chapter 5** Application of boundary layer theory to the prediction of unstalled curved diffuser performance - Including effects of wall curvature and end wall effects.

Chapter 6** Effects of Inlet Conditions on Performance - Inlet boundary layer, turbulence and flow distortions.

Section III**

Rational Design of Axi-Symetric Diffusers - Conical, Annular, etc.

Section IV*** (Kuhne, ? and Johnston)

Rational Design of Rotating Diffuser Passages - In particular the design of unstalled blade passages in radial and mixed flow turbomachine impellers.

Section V**

Generalization of Methods of Rational Passage Design to Complex Situations.

Section VI**

More general discussion of flow with large stalled regions; including not only diffuser problems but also many wake, sudden enlargement and base pressure problems.

** Contemplated future work not presently scheduled.

*** Work here has not progressed far enough to outline in detail.

APPENDIX III Honors, Awards, Communications

The work of MD-4 (AFOSR-TN-58-637) was awarded the 1959 Melville Medal of the ASME for, "The Best Technical Paper Presented to the Society During the Previous Year".

Invited Seminars on various aspects of the work have been given at many universities and industrial concerns; included among these are:

Universities

University of California, Berkeley
University of California, Los Angeles
California Institute of Technology
Dartmouth
Harvard University
University of Illinois
The Johns Hopkins University
University of Maryland
Massachusetts Institute of Technology
University of Michigan
New York University
Pennsylvania State

Corporations

General Electric, 5 Divisions and Laboratories
General Motors Research Laboratory
Carrier Corporation
IBM (Endicott)
Westinghouse
Worthington